Vol. 48 No. 1 Journal of the Communications Research Laboratory March 2001
Printed in Tokyo, Japan pp. 143−150

4.4 Radar Observations of Near Earth Asteroids 6489 Golevka and 4197 (1982 TA)

By

Yasuhiro KOYAMA, Junichi NAKAJIMA, Mamoru SEKIDO,
Makoto YOSHIKAWA, Akiko M. NAKAMURA, Hisashi HIRABAYASHI,
Tatsuaki OKADA, Masanao ABE, Toshiyuki NISHIBORI,
Tetsuharu FUSE, Steven J. OSTRO, Dennis CHOATE,
Reginald A. CORMIER, Ron WINKLER, Raymond F. JURGENS,
Jon D. GIORGINI, Keith D. ROSEMA, David L. MITCHELL,
Donald K. YEOMANS, Martin A. SLADE, and Alexander L. ZAITSEV

ABSTRACT

Radar observations of two near-Earth asteroids were performed using a bi-static radar technique with Kashima 34-m antenna and Usuda 64-m antenna as receiving stations and Goldstone 70-m antenna as a transmitting station. The asteroid 6489 Golevka was observed on June 15, 1995 when its distance from the Earth became 0.048 AU and the radar echo from the asteroid was detected from the data observed with Kashima 34-m antenna. The success of the trans-continental bistatic radar observations became the first detection of a radar echo from a solar system object beyond Moon in Japan. The asteroid 4197 (1982 TA) was observed on October 24, 1996 when its distance to the Earth became 0.086 AU. The radar echo signal from the asteroid was detected from both of the data observed at Kashima and at Usuda. The received signal was coherently sampled and recorded at both stations. By using these data, interferometric data analysis was examined.

Keywords: Earth and Planetary System: Radar, Near Earth Asteroids, Interferometry

1. Introduction

Radar technique has established its role as a powerful tool in exploring solar system bodies through over three decades of its long and fruitful history[1]. Until recently, radar was the most powerful method to investigate geometry and the surface properties of asteroids. Even in this era when spacecraft observations have become a reality, importance of the radar technique has not faded away because the opportunities for radar observation are more frequent than costly space missions. However, in Japan, there had been no experience of radar observation of planetary bodies until our attempt to detect radar echoes from the near-Earth asteroid 6489 Golevka (1991 JX). The asteroid approached the Earth to the minimum distance of 0.034 AU in June 1995. Bi-static radar observations were performed with the 34-m antenna of Communications Research Laboratory at Kashima Space Research Center (Ibaraki, Japan) as a receiving station and the 70m antenna of Jet Propulsion Laboratory at Goldstone Deep Space Communications Complex (California, USA) as a transmitting station. The radar echo was successfully detected from the observed data and the asteroid became the first solar system object beyond Moon ever observed by the radar technique from Japan. The radar echo signal from the asteroid was also received by the 70-m antenna at Evpatoria Deep Space Communication Complex in Crimea[2]. The asteroid was named after the successful radar observations by taking initial characters of the three involved ground antennas at Goldstone (GOL), Evpatoria (EV), and Kashima (KA).

The other asteroid 4197 (1982 TA) approached the Earth to the minimum distance of 0.085 AU in October 1996. The asteroid was observed by transcontinental bistatic radar technique again by the 34-m antenna at Kashima and by the 64-m antenna of the Institute of Space and Astronautical Science at Usuda Deep Space Center (Nagano, Japan). By observing the same radar echo signal at two separated stations, interferometric data processing became possible. The minimum fringe spacing of an interferometer is achieved when the direction of the observed object becomes perpendicular to the direction of the baseline. The distance between Kashima and Usuda stations is 208 km and the minimum fringe spacing of the Kashima-Usuda baseline at 8510-MHz signal frequency is calculated as 34.9 milli-arcsecond. This fringe spacing corresponds to the size of the object of 2.14 km at 0.085 AU of distance. If the size of the object is smaller than the fringe spacing, the cross power spectrum of the received signals at two stations should give a one dimensional Fourier coefficient in the direction parallel to the baseline. To obtain the cross power spectrum, received signals were sampled and recorded coherently at both stations using Digital Audio Tape (DAT) data recorder systems by synchronizing the internal clock of the recorder with external frequency reference signals from hydrogen maser frequency standard systems.

2. Observations

2.1 Asteroids

The asteroid 6489 Golevka (1991 JX) was discovered by Eleanor Helin on May 9, 1991 with the 0.46-m Schmidt telescope at Palomar Observatory (California, USA). The minimum distance from the Earth in the second approach was about 0.034 AU. The asteroid is categorized as an Apollo object and has an Earth-crossing orbit with a perihelion distance of 1.012 AU and an eccentricity of 0.5975. Radar observations at Goldstone[3] were carried out during the period from June 3 to June 15, and the Goldstone-Kashima bistatic observations were done on June 15. The geocentric distance of the asteroid when the observations were done at Kashima was about 0.048 AU.

The other asteroid 4197 (1982 TA) was discovered by Eleanor Helin and Eugene Shoemaker on October 11, 1982 with the 1.2-m Schmidt telescope at Palomar Observatory. The asteroid is categorized as an Apollo object and has an Earth-crossing orbit with a perihelion distance of 0.5166 AU and an eccentricity of 0.7555[4]. The asteroid approached the Earth to the geocentric distance of 0.085 AU on October 25, 1996. The radar observations to the asteroid were performed at Kashima and at Usuda on October 24, 1996, when the geocentric distance was 0.086 AU.

2.2 Transmission System

Throughout the asteroid radar observations of 6489 Golevka and 4197 (1982 TA), a high power radio signal was transmitted from the 70-m antenna at Goldstone either with an unmodulated continuous sine wave form (CW) or in a phase-modulated wave form. In the latter case, time codes are embedded in the transmitted signal to obtain ranging information, whereas the signal-to-noise ratio of the radar echo signal decreases due to the time modulation. Therefore, the transmitted signal was kept unmodulated to maximize the signal-to-noise ratio of the radar echo signal in the received signal during the observations at Kashima. The frequency of the transmission signal was smoothly controlled so that the echo frequency at the Goldstone-70m station becomes constant, but the echo frequency at Kashima-34m station slowly changed with time near 8510.0 MHz due to the Doppler effect. The signal was transmitted in left hand circular polarization (LHCP) and the power of the transmission P_{tx} was 450 kW. The gain of the transmission antenna G_{tx} was 74.3 dB in the X-band.

2.3 Receiving and Data Acquisition System

Figure 1 illustrates the configuration for the receiving and data acquisition system at Kashima. Both right hand circular polarization (RHCP) and LHCP signals were received and recorded. Signals from the polarizer of the X-band feed system were amplified with two independent low noise amplifiers (LNA) and converted to an intermediate frequency (IF : 100-600 MHz) by down converters. Local frequency of the down converters is 8080 MHz and the received signal at 8510 MHz becomes 430 MHz at this stage. The IF signals were then converted to baseband frequency (DC-2 MHz) with image rejection mixers (IRM) with local frequency of 429.99 MHz. Finally the baseband frequency signals were filtered with low pass filters (LPF) in the DAT data recorder unit. The cut off frequency of the LPFs is 20 kHz whereas the sampling rate of the A/D is 48 kHz with the sampling resolution of 14 bits. A 10 MHz reference frequency signal from the hydrogen maser system was provided to both down converters and IRMs. In the observations to the asteroid 4197 (1982 TA), the frequency standard signals were provided to the DAT recorders so that coherent recording of the radar echo signals became possible.

Calibration observations of the receiving system were performed before the radar observations. To measure receiver noise temperature T_{rec} and system noise temperature T_{sys}, the signal power of the receiver output was measured at the IF stage by a spectrum analyzer with the bandwidth set to 1 MHz. The power was measured with three different signal sources, i.e. a 'cold' load : P_{cold}, a 'hot' load : P_{hot}, and the 'sky' at the zenith : P_{sky}. The cold load and hot load are wave guide terminators located in the outer stage (~90 K) of the dual stage dewar and in the room temperature environment, respectively. From the measurements, receiver noise temperature T_{rec} can be determined by

$$T_{rec} = \frac{T_{hot} - (P_{hot}/P_{cold})\tilde{T}_{cold}}{(P_{hot}/P_{cold}) - 1}, \qquad (1)$$

where $\tilde{T}_{cold}$ is the effective temperature of the cold load

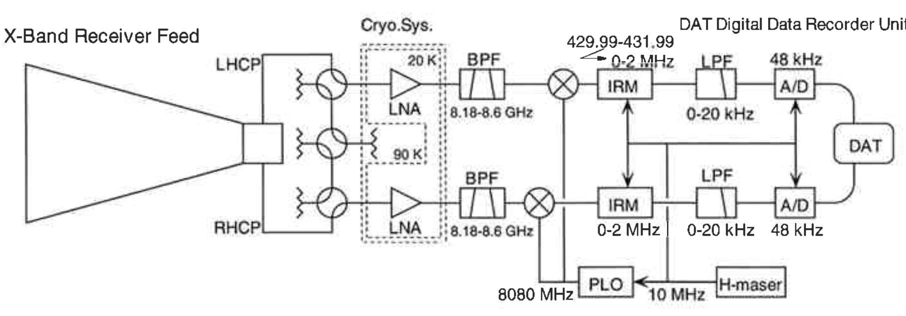

Fig. 1 Configuration of the asteroid radar observation system at Kashima. Both RHCP and LHCP signals received were recorded by a DAT data recorder unit. Cold load and hot load were used for calibration measurements. Frequency range at various stages are also shown in the figure.

Table 1 Calibration measurements of the receiver noise temperature T_{rec} and system noise temperature T_{sys}. T_{hot} and T_{cold} are physical temperatures of the hot load and cold load respectively. P_{hot}, P_{cold}, and P_{sky} are the signal power when the hot load, the cold load, and the sky at the zenith have been connected to the input of the low noise amplifier, respectively.

Polarization	T_{hot} K	T_{cold} K	P_{hot} dBm	P_{cold} dBm	P_{sky} dBm	T_{rec} K	T_{sys} K
RHCP	294.54	93.35	−38.86	−43.14	−46.38	22.0	56.0
LHCP	294.54	93.37	−46.00	−50.52	−53.58	12.1	53.5

Table 2 Calibration measurements for the gain of the receiving system G_{rec}. P_{on} and P_{off} are power levels when the antenna is tracking a strong radio source Cas-A and when it is not tracking any source, respectively.

Polarization	P_{on} dBm	P_{off} dBm	G_{rec} dB
RHCP	−36.070	−38.442	65.4
LHCP	−34.333	−36.814	65.5

corrected for loss L through the route from the cold load to the LNA by the equation

$$\tilde{T}_{cold} = (1-L)\,T_{cold} + L\,T_{amb}. \quad\cdots\cdots(2)$$

L has been measured as 0.014. T_{amb} is ambient temperature which is equal to T_{hot}. The system noise temperature T_{sys} can then be determined by

$$T_{sys} = (T_{hot} + T_{rec})\frac{P_{sky}}{P_{hot}}. \quad\cdots\cdots(3)$$

Table 1 shows the T_{rec} and T_{sys} values measured before the radar observations toward 6489 Golevka. The gain of the receiving system G_{rec} was then measured by using CAS-A as a strong calibration source. Provided that the power is at P_{on} when the antenna is tracking the source and the power is at P_{off} when the antenna is offset from the source, G_{rec} can be determined by

$$G_{rec} = \frac{8\pi k_B T_{sys}}{\lambda^2 J}\left(\frac{P_{on}}{P_{off}} - 1\right), \quad\cdots\cdots(4)$$

where k_B is Boltzmann's constant, λ is the wavelength, and J is the effective flux density of a strong radio source Cas-A corrected for the beam size of the 34-m antenna and the effect of secular decrease of the flux density which is calculated as $328 \times 10^{-26}\ \mathrm{Wm^{-2}Hz^{-1}}$[5]. Table 2 shows the values of G_{rec} calculated from the observations performed before the radar observations toward 6489 Golevka.

3. Results and Discussions

After the observations for the asteroid 6489 Golevka, the recorded data were transferred to a UNIX workstation via a GP-IB communication interface. Since the speed of data transfer was much slower than the original data rate, the data was divided into small blocks which fit the size of the buffer memory on the interface board. Later, for observations of 4197 (1982 TA), data transmission speed became considerably faster through use of a SCSI interface. After the observed data were transferred, the Fourier transforms of the data, $\mathcal{F}_i(f)$, were calculated. The power spectrum, $\mathcal{P}(\Delta f)$, was then calculated from

$$\mathcal{P}(\Delta f) = \frac{1}{\sigma}\left(\sum_{i=1}^{N}[\mathcal{F}_i(\Delta f + f_0(t_i))\mathcal{F}_i^*(\Delta f + f_0(t_i))] - \mathcal{P}_0\right) \quad\cdots\cdots(5)$$

where Δf is the frequency offset from the central estimated frequency of the radar echo f_0. $\mathcal{P}_0$ and σ were introduced to normalize the power spectrum. These values were given by the average and standard deviation of the power spectrum evaluated in the frequency range where the radar echo signal was not present. The value of f_0 was determined based on a table of nominal orbit predicts, output at 10 minutes time steps. Figure 2 shows how f_0 changed over time in the observations of the asteroid 6489 Golevka. The solid line in Figure 2 is a fourth order polynomial which fits the f_0 calculated at intervals of 10 minutes. The value of the polynomial was actually used for the f_0 in equation (5). The order of the polynomial was chosen as 4 so that the residual of the fit would not exceed 0.1 Hz.

The inverse of time length of the data segment used to calculate $\mathcal{F}(f)$ determines the frequency resolution. A finer frequency resolution requires longer data to be averaged. Figure 3 shows the normalized power spectrum of the RHCP signal received during the observations of the asteroid 6489 Golevka. The frequency resolution of the power spectrum is 0.2 Hz and the received signal was integrated over 57 minutes from 15:28 UT on June 15, 1995. A radar echo signal is evident with a peak amplitude of 8.4. Figure 4 shows the normalized power spectrum of the RHCP signal received during the bservations of the asteroid 4197 (1982 TA). The frequency resolution of the power spectrum is 11.7 Hz and the signal was integrated over 74 minutes from 08:30 UT on October 24, 1996. The radar echo is evident both in the observed data at Kashima and at Usuda with the peak amplitudes of 7.2 and 9.2, respectively. The LHCP observation data were processed in the same way, but the radar echo could not be identified. Because the radar echo signal in the opposite circular polarization of the transmitted signal is much stronger than that of the same circular polarization, the result is consistent with the expectation.

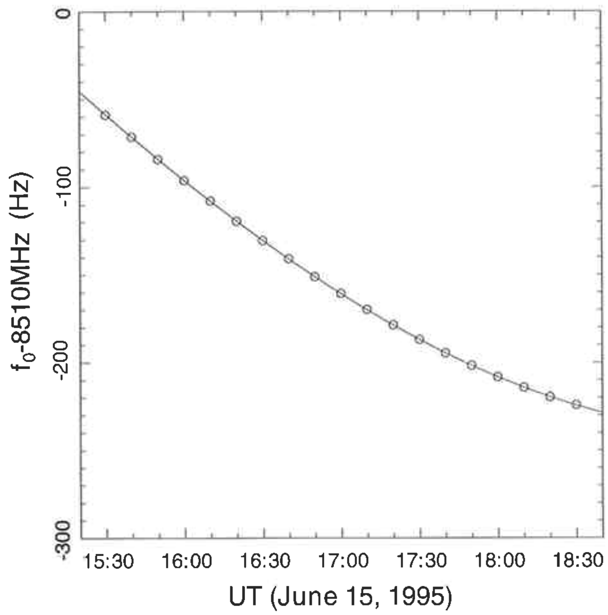

Fig. 2 Estimated central radar echo frequency f_0. Vertical axis is f_0-8510 MHz expressed in Hz. f_0 was estimated from refined orbit elements at intervals of 10 minutes and is shown by open circles. Solid line is the best fit to the estimated f_0 by a fourth order polynomial.

The total power of a radar echo signal is proportional to an effective cross section, $\rho_r A$, of a target asteroid where ρ_r is a radar albedo and A is a cross section of the asteroid. The relation can be expressed as

$$P_{rec} = \frac{P_{tx} G_{tx} G_{rec} \rho_r A \lambda^2}{4\pi R_{tx}^2 \cdot 4\pi R_{rec}^2 \cdot 4\pi}. \qquad (6)$$

Here, λ is the wavelength of the radar signal, P_{tx} is the transmitting signal power, G_{tx} is the gain of the transmitting antenna, R_{tx} is the distance of the asteroid from the transmitting station, P_{rec} is the received signal power, G_{rec} is the gain of the receiving antenna given in equation (4), and R_{rec} is the distance of the asteroid from the receiving station. On the other hand, the standard deviation for power spectrum of noise, N, can be evaluated by equation,

$$N = k_B T_{sys} \sqrt{\frac{B}{t}}, \qquad (7)$$

where k_B is Boltzmann's constant, T_{sys} is the system noise temperature of the receiving station given in equation (3), B is the frequency resolution of the power spectrum, and t is the integration time. The normalized power spectrum of the received data defined by equation (5) can then be evaluated as

$$\sum_{\Delta f} \mathcal{P}(\Delta f) = \frac{P_{rec}}{N}, \qquad (8)$$

where summation of the left hand side of the equation should be done for the frequency range where radar echo signal is present. From Figure 3, the region where

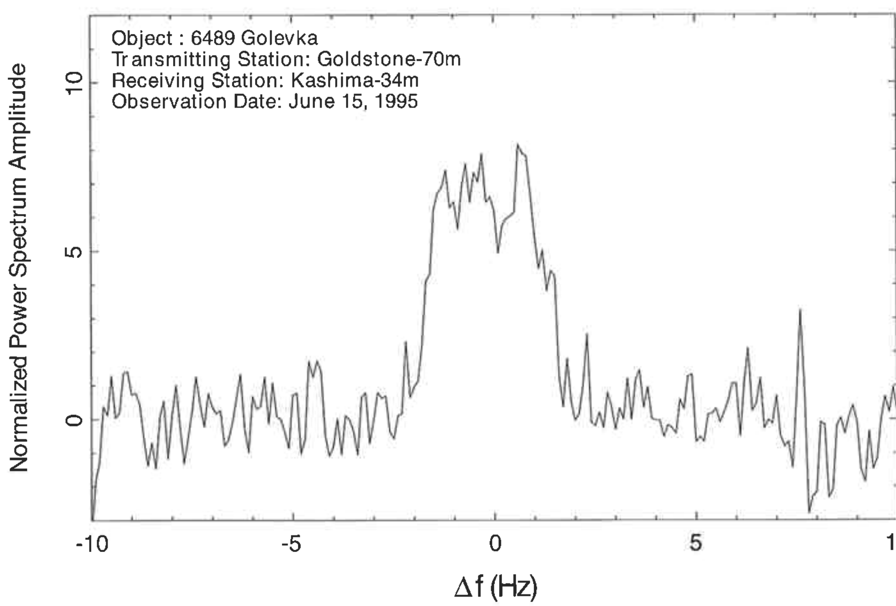

Fig. 3 Normalized amplitude of the RHCP power spectrum averaged for 57 minutes from 15:28 UT to 16:25 UT on June 15, 1995 with a frequency resolution of 0.2 Hz. The power spectrum has been normalized to make average and standard deviation at a frequency where no signal is present become 0 and 1 respectively.

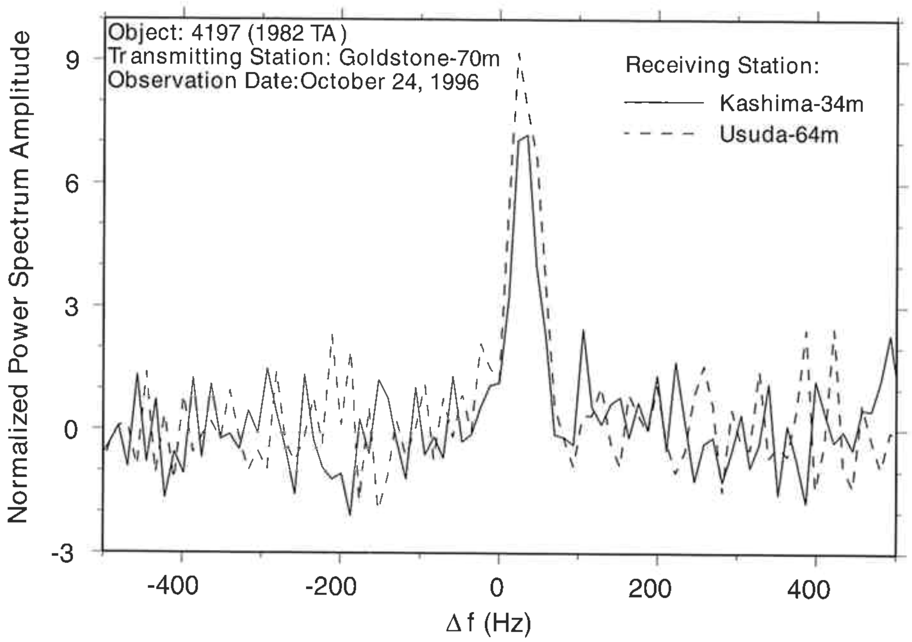

Fig. 4 Normalized amplitude of the RHCP power spectrum averaged for 74 minutes from 08:30 UT to 09:45 UT on October 24, 1996 with a frequency resolution of 11.7 Hz. The power spectrum has been normalized to make average and standard deviation at a frequency where no signal is present become 0 and 1 respectively. The power spectrum of the data received at Kashima is shown with the solid line, whereas the Usuda data is shown with the dashed line.

$\mathcal{P}(f)$ exceeds 2, and hence radar echo signal is considered to be present, is $-1.8(\mathrm{Hz}) \leq \Delta f \leq 1.5(\mathrm{Hz})$. By integrating $\mathcal{P}(f)$ for the range, the total power of the radar echo signal can be evaluated as $211 \times N$. By using the various parameters already given in the previous sections, $\rho_r A = 0.063$ (km^2) is obtained. The effective diameter of 6489 Golevka has been estimated to be no greater than 600 m[3]. Thus our Goldstone-Kashima estimate of the radar cross section implies a radar albedo of at least 0.22, which is considerably larger than the typical values reported to date for small asteroids. The same procedure to the power spectrum in the Figure 4 gives $\rho_r A = 0.98$(km^2) and a radar albedo of 0.078 for the asteroid 4197 (1982 TA) assuming the diameter of the asteroid is 4 km based on the estimation from optical observations.

The maximum dimension of the asteroid perpendicular to its apparent rotation axis D and its apparent rotation angular velocity ω can be related to Doppler frequency width W as,

$$W = \frac{D\omega \sin\theta}{c} f_0. \qquad (9)$$

where f_0 is the frequency of the central frequency of the received echo signal, c is the velocity of light, and θ is the angle between the apparent rotation axis and the direction towards the receiving station seen from the asteroid. From Figure 3, the lower edge of the radar echo signal is between -1.9 Hz and -1.8 Hz, whereas upper edge is between 1.5 Hz and 1.6 Hz.

Thus the frequency width of the radar echo can be estimated as $W = 3.4 \pm 0.1$ Hz. The rotation period of the asteroid has been determined from optical observations as 6.02 hours[2]. Therefore, we obtain $D \sin\theta = 0.41 \pm 0.01$km. This result is consistent with the diameter of the asteroid if θ is no more than 40 degrees. Applying the same procedure to the asteroid 4197 (1982 TA), θ is evaluated as 4.2 ± 0.8 km. This value is consistent with the estimated size from the optical observations if θ is close to 90 degrees, i.e. the rotation pole of the asteroid is close to perpendicular to the line of sight.

Finally, the cross power spectrum of the two recorded data at Kashima and Usuda was calculated. Figure 5 shows the results for three different time lengths of coherent integration lengths, t_i. The cross power spectrum was integrated for the time t_i and then the amplitude of the cross power spectrum was averaged for 74 minutes from 08:30 UT on October 24, 1996. As shown in Figure 5, the averaged amplitude of the radar echo in the cross power spectrum decreases rapidly when the coherent integration time is extended. Several parameters such as Doppler frequency shifts and clock rates of the observation sites were adjusted but the results were the same. Since the size of the asteroid is larger than the fringe spacing, it is considered that the interferometric fringe amplitude becomes very small.

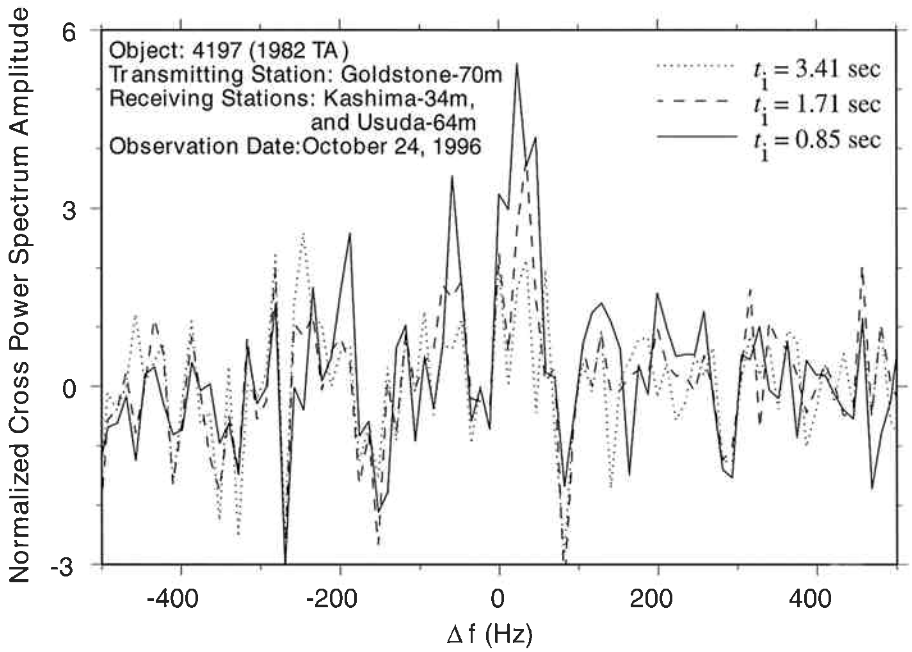

Fig. 5 Normalized amplitude of the RHCP cross power spectrum of the recorded data at Kashima and Usuda. Three different time is taken for the coherent integration time, $t = i$, and the amplitude of the cross power spectrum was averaged for 74 minutes from 08:30 UT on October 24, 1996. The frequency resolution is 11.7 Hz.

4. Conclusions

The radar echo signals from the asteroid 6489 Golevka were detected and analyzed from the data obtained by the 34-m antenna at Kashima. It became the first successful radar observations beyond the Moon in Japan. Although the duration of observations was short, the capability of the observation facilities for asteroid radar experiments was satisfactorily demonstrated. Based on this encouraging success, opportunities for further radar experiments will be considered for a variety of near-Earth asteroids. Through this actual experience we have learned many useful things needed for future radar observations. First of all, a sufficient period of observation is required covering at least a period of rotation. Longer periods of observations should allow us to estimate the rotation period independently from the radar data. Secondly, time code modulation should be applied to the transmitting signal to obtain range information. By using the modulation technique, radar echo signals can be resolved in terms of range.

In the observations to the asteroid 4197 (1982 TA), the interferometric data analysis was examined. Although radar echo was detected from both of the observation data recorded at Kashima and Usuda, the cross power spectrum could not be evaluated when the coherent integration time was extended more than 3 seconds. The size of the asteroid was larger than the fringe spacing and the useful information could not be obtained from the cross power spectrum. To obtain useful information from the interferometric radar observations, it is necessary that the object approach the Earth closely enough and there be a short enough baseline available so that the fringe spacing becomes larger than the size of the asteroid.

Acknowledgements

We would like to express our gratitude to all of our colleagues at the Communications Research Laboratory, the Institute of Space and Astronautical Science, and the Jet Propulsion Laboratory who made this radar experiment possible. In addition, we would also like to thank Dr. E. F. Helin who discovered the asteroid and proposed the name 'GOLEVKA' (original proposal was 'GEK' actually) to the Minor Planet Center of the International Astronomical Union to honor the successful radar observations at Goldstone, Evpatoria, and Kashima. Part of this research was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

(1) S. J. Ostro, "Planetary radar astrometry", Rev. Modern Phys., vol. 65, pp.1235-1279, 1993.

(2) A. L. Zaitsev, S. J. Ostro, S. P. Ignatov, D. K. Yeomans, A. G. Petrenko, D. Choate, O. K. Margorin, R. A. Cormier, V. V. Mardyshkin, R. Winkler, O. N. Rghiga, R. F. Jurgens, V. A. Shubin, J. D. Giorgini, A. P. Krivtsov, K. D. Rosema, Y. F. Koluka, M. A. Slade, A. L. Gavrik, V. B. Andreev, D. V. Ivanov, P. S. Peshin, Y. Koyama, M. Yoshikawa,

and A. Nakamura, "Intercontinental bistatic radar observations of 6489 Golevka (1991 JX)", Planet. Space Sci., vol. 45, no.7, pp.771-778, 1997.

(3) R. S. Hudson, S. J. Ostro, R. F. Jurgens, K. D. Rosema, J. D. Giorgini, R. Winkler, R. Rose, D. Choate, R. A. Cormier, C. R. Franck, R. Frye, D. Howard, D. Kelley, R. Littlefair, M. A. Slade, L. A. M. Benner, M. L. Thomas, D. L. Mitchell, P. W. Chodas, D. K. Yeomans, P. Palmer, A. Zaitsev, Y. Koyama, A. Nakamura, A. W. Harris, and M. N. Meshkov, "Radar Observations and Physical Modeling of Asteroid 6489 Golevka", Icarus, vol. 148, no.1, pp.37-51, 2000.

(4) J. Graham, "Asteroid Discovery 1982TA", Foundation News, World Space Foundation, Oct. 1982.

(5) W. A. Dent, Astrophys. J., vol. 188, p. L11, 1974.